Complementary Pathways to Decarbonization: The Social and Economic Implications of Integrating EVs and Renewable Fuels in the U.S. Auto Industry

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As the world becomes more technologically advanced day by day, there grows concerns over the increasing demand for energy and the resulting environmental impacts. Due to these trends, global initiatives have been set over concerns about greenhouse gas emissions, which heat our atmosphere (United Nations, 2020). These gas emissions cause this heating effect by acting like a blanket in our atmosphere, insulating heat by absorbing the solar energy the Earth absorbs, preventing it from going out into Space (United Nations, 2020). One way in which governments across the world have intervened through policy is in setting initiatives for the transportation sector, and more specifically, the electric vehicle (EV) industry. Many of these initiatives entail the replacement of internal combustion engine (ICE) vehicles by some percentage by a certain year, with some countries setting goals for the complete replacement of ICE vehicles with EVs (International Energy Agency, 2023). In analyzing these trends in government policy, issues arise in social, economic, and environmental equity in accordance with an increase in production scale for EVs. By applying the economies of scale framework to the EV and renewable fuels industry, a comparison can be drawn between the two, allowing for a more in-depth structure as to how our world should go about the clean energy transition.

Research Methodology

To analyze the social and economic implications of integrating renewable fuel sources within the auto industry in the United States, the following question is proposed: "What are the comparative advantages and challenges of electric vehicle adoption versus renewable fuel implementation as pathways to decarbonizing the transportation sector?" This research employs a documentary analysis methodology, applying Stigler's (1958) economies of scale framework to evaluate how production scale affects costs, resource demands, and market viability for both industries. Data is gathered from government reports (International Energy Agency, EPA, Department of Energy), academic literature, and industry analyses, which all help to provide a comprehensive analysis. This analysis compares current price differentials, projects future resource requirements, evaluates policy impacts, and assesses social equity implications for both decarbonization pathways. The remainder of this paper discusses the background information for transportation emissions and decarbonization approaches, analyzes literature on economies of scale theory and its application to energy transitions, describes comparative advantages and limitations of each pathway, and concludes with policy recommendations for an integrated approach to transportation decarbonization.

Carbon Context

In the United States specifically, 28% of the greenhouse gasses emitted into the atmosphere are through transportation, a sector that is more easily transitioned into renewable energies than others, like our power grid (US EPA, 2015). Vehicles run on a variety of fuels from gasoline to diesel, so by replacing these fuels with a green solution, such as biodiesel made from waste cooking oils, society can cut down on one of the largest contributors of greenhouse gas emissions. The other outlook on solving the emissions problems across the globe is in ramping up EV production. As it currently stands, however, a compact SUV that is an EV is on average 32.5% more expensive than a compact SUV that has an ICE (O’Dell, 2024). This cost disparity poses some problems moving forward for green energy transition initiatives that include the replacement of ICE vehicles with EVs, as lower and middle-class people cannot or aren’t willing to pay such a premium. This is fixed if EVs are able to reach an economy of scale, where they would be cheaper than ICE vehicles on the market, however, there exists key issues for the EV industry to reach this scale. Primarily, the growing demand for rare earth metals. As battery demand is expected to grow nearly 40 times from 2020 to 2040, the consequent baseline metal demand is projected to grow 30 times in that same period (International Energy Agency, 2021). This demand increase is a big problem for the EV industry, as increasing the scale of production will cause a resulting increase in demand for the inputs, creating a cancellation effect in pricing. An alternative solution for decarbonizing the transportation sector is through the renewable fuels industry reaching an economy of scale. As of a 2024 study on consumer fuel price indexes, renewable biodiesel costs on average $0.41 more than its fossil fuel counterpart (US Department of Energy, 2024). However, this price gap can be lowered through government policy intervention and market diversity, where subsidies, contracts, and a free open market help renewable fuels to reach an economy of scale.

With renewable fuels reaching the required scale to lower prices below their fossil fuel counterparts, the green energy transition is facilitated by the replacement of renewable fuels across the board. This would result in a more socially, environmentally, and economically equitable transition, as people would not have to go out and buy a new EV to complete the transition, fueling would be cheaper, and rare earth metals would be conserved. If society wants to complete the green energy transition, a dual approach must be considered going forward.

Global Stage and Economies of Scale

The economies of scale concept, while not directly named as such by Adam Smith, finds its beginnings in his work "The Wealth of Nations" (1776). Smith's famous pin factory example illustrated how division of labor dramatically increased productivity, with ten specialized workers producing "upwards of forty-eight thousand pins in a day" compared to perhaps not even twenty pins if each worker performed all tasks independently. This specialization principle extends beyond individual factories to entire industries and markets, where increased production volumes allow for greater specialization, lower per-unit costs, and enhanced efficiency. Smith recognized that these productivity gains were limited by "the extent of the market," acknowledging that sufficient demand must exist to support specialized production at scale. This framework provides context for understanding why renewable fuel technologies like biodiesel face higher costs until they achieve sufficient market penetration and production volume to reach economies of scale.

According to the International Energy Agency, renewable energy sources accounted for 26.49% of global electricity generation in 2019. In 2000, this share was 18.68%, which exemplifies the global transition to renewable energy sources in the 21st century (International Energy Agency, 2021). Despite this continuous growth in the renewables sector, prices for alternative fuels continue to be more expensive than conventional fossil fuels (US Department of Energy, 2024). Specifically, biodiesel on average costs $0.41 more per gallon than conventional diesel (US Department of Energy, 2024). This is due to the economies of scale framework, which simply describes that the cost of production decreases as the scale of production increases. However, much more comes into play within this framework, such as government policy, supplier dynamics, and market diversity, which all factor into economies of scale. Additionally, there exists a “diseconomy of scale” if the costs of production increase with the scale of production, so a balance must be present between all the factors. For example, production scale increases for a given biodiesel plant, but this requires the company to look for additional suppliers to account for the new production level, resulting in a substantial increase in input costs that outweighs the new production scale, thus moving the plant into a diseconomy of scale. However, this issue can be circumvented with government policy such as manufacturing subsidies, allowing a given company to reach an economy of scale without incurring as much of the costs associated with a larger scale of production.

As it currently stands, with renewable fuels being more expensive than traditional fossil fuels for consumer vehicles, the renewables industry hasn't been able to reach an economy of scale. This is critical, as countries across the globe have set initiatives for the replacement of ICE vehicles with EVs, with some countries like Chile fully banning the sale of ICE vehicles by 2040 (International Energy Agency, 2023). These initiatives cannot be met if the market stands as it is, with EVs costing more on average than ICE vehicles, unless government intervention takes place. Instead of advocating for a single approach towards decarbonization through EVs, future policy initiatives should be shifted to allow for both EVs and renewable fuels to be implemented. This dual approach would allow the ICE auto industry to not only survive, but also prevent the need for lower and middle-class people to go out of their way to purchase an EV. By reaching an economy of scale in the renewable industry, a more socially equitable transition can take place towards a green and net-carbon-neutral society.

Scholarly debate in this field leans towards the complete replacement of EVs over ICE vehicles, as they are not only more efficient than ICE vehicles from a mechanical standpoint but also don't use fossil fuels. However, additional factors such as rare earth metal consumption, electrical grid supply, and cost are not accounted for. A full hybrid EV requires, on average, 4.4kg of rare earth metals to produce, while ICE vehicles only require 0.44kg on average (Alonso et al., 2012). This will be a pressing issue moving forward as the EV industry tries to reach an economy of scale; the production scale will go up, but so will rare earth metal demand and thus input costs. Demand for some rare earth metals is projected to increase 40X by the year 2040, a year when many climate policy initiatives are supposed to be met (International Energy

Agency, 2021). This will make it very hard for the EV industry to reach economies of scale, as the cost of sourcing rare earth metals will only grow more and more expensive. There needs to be an alternative outlook and initiatives set towards making the renewable fuels industry reach an economy of scale. The inputs for renewable fuels, such as biodiesel, typically come from waste streams like spent cooking oil or animal fats. If demand increases for these waste-stream inputs as the production scale for biodiesel increases, one would expect that the consequent price increase would not be as aggressive as in the case of rare earth metals. Because of the inputs for production, it is much easier for the renewable fuel industry to reach an economy of scale than that of the EV industry.

Economies of Scale Framework Applied to Transportation Decarbonization

The application of Stigler's (1958) economies of scale framework to transportation decarbonization pathways reveals significant distinctions in how the EV and renewable fuels industries might achieve cost competitiveness with conventional alternatives. Based on this framework, as production scale increases, both industries should theoretically experience decreasing per-unit costs, but the analysis reveals different trajectories based on resource constraints, policy environments, and market structures (Stigler 1958).

Economic Analysis of EV and Renewable Fuel Markets

The current market positioning shows price premiums for both alternative technologies described in this paper. Electric vehicles currently command a 32.5% price premium over comparable internal combustion engine vehicles (O'Dell, 2024), while renewable biodiesel costs approximately $0.41 more per gallon than conventional diesel (US Department of Energy, 2024).

These price differentials create significant barriers to adoption, particularly for lower and middle-income consumers who comprise much of the vehicle market.

When projecting future cost trajectories, however, the two pathways diverge considerably. For EVs, battery production represents approximately 40% of the total vehicle cost, which relies heavily on rare earth metals and other critical minerals. With demand for these materials projected to increase by 30-40 times from 2020 to 2040 (International Energy Agency, 2021), the input costs for EV manufacturing will likely face significant upward pressure, potentially offsetting manufacturing efficiencies gained through increased production volumes.

The economic analysis by Rapson and Muehlegger (2021) acknowledges various challenges facing the EV industry but notably fails to adequately address the supply chain constraints of rare earth metals and critical minerals. This gap in the literature underscores a potential blind spot in current policy planning, as many analyses assume that an increased production scale will automatically lead to lower costs without considering resource constraints that might bottleneck this trend.

In contrast, the renewable fuels industry, particularly biodiesel derived from waste streams such as spent cooking oil, faces a different economic trajectory. The primary inputs for waste-derived biodiesel are largely byproducts from other industries that would otherwise be discarded and put into landfills. As Kesan et al. (2017) demonstrate in their analysis of the Renewable Fuel Standard's impact, policy interventions have successfully stimulated production scale increases in the biofuel sector, though the full potential for cost reduction has not yet been realized due to inconsistent policy support.

Recent developments in adjacent sectors provide instructive parallels. Baan (2025) outlines how industrial policy is shaping new fuel landscapes for hard-to-electrify industries like aviation, where sustainable aviation fuels are beginning to achieve economies of scale through consistent policy support and industry investment. This pattern suggests that similar approaches could accelerate cost reductions in automotive biofuels.

Resource Demand and Environmental Implications

The resource demands of both transition pathways present contrasting environmental implications. As documented by Alonso et al. (2012), a full hybrid EV requires approximately 4.4kg of rare earth metals to produce, compared to just 0.44kg for ICE vehicles. This tenfold increase in rare earth metal consumption represents a significant environmental consideration for the adoption of EVs. The mining and processing of these materials often involves substantial environmental impacts, including habitat destruction, water pollution, and energy-intensive extraction processes.

Furthermore, the International Energy Agency's (2021) projection of a 40-fold increase in demand for some critical minerals by 2040 raises serious questions about the sustainability of a transition strategy heavily dependent on EVs. While manufacturers are working to reduce reliance on the most constrained materials through battery chemistry innovations, the scale of projected demand suggests that resource limitations could become a binding constraint on EV industry growth.

Conversely, renewable fuels derived from waste streams offer environmental benefits beyond carbon reduction. By repurposing materials that would otherwise contribute to waste management challenges, waste-derived biodiesel represents a form of circular economy that addresses multiple environmental objectives simultaneously. Unlike cultivated biofuel feedstocks that may compete with food production or contribute to land-use changes, waste-derived biodiesel avoids these negative externalities while still delivering carbon-reduction benefits.

The environmental considerations are further complicated by lifecycle emissions consideration. While EVs produce zero tailpipe emissions, their overall carbon footprint is influenced by the carbon intensity of electricity generation and manufacturing processes. The World Energy Balances overview (International Energy Agency, 2021) shows increasing trends in renewable energy implementation for grid electricity generation, which would improve EV lifecycle emissions over time. However, the comprehensive environmental accounting must include the impacts of resource extraction and manufacturing, which remain substantial for EVs.

Policy Environment and Market Intervention

Current government policy across many countries has predominantly focused on encouraging EV adoption through purchase incentives, charging infrastructure investments, and, in some cases, planned phase-outs of ICE vehicle sales. The International Energy Agency's policy developments report (2023) highlights how countries like Chile have fully banned the sale of ICE vehicles by 2040, reflecting an implicit assumption that electrification represents the optimal pathway to transportation decarbonization.

However, this approach may overlook the potential of renewable fuels to offer a complementary decarbonization pathway. The empirical study by Kesan et al. (2017) on the impact of the Renewable Fuel Standard demonstrates how policy interventions can effectively stimulate production and market development for alternative fuels. Their analysis suggests that more consistent and targeted policy support could accelerate cost reductions and market integration for renewable fuels.

The economies of scale framework suggests that targeted policy interventions could accelerate the development of the renewable fuels market, potentially achieving carbon reductions more quickly and equitably than an EV-only targeted strategy. Production subsidies for waste-derived biodiesel could help producers achieve the scale necessary to reduce costs below conventional diesel, creating a market-driven incentive for adoption. Similarly, fuel blending requirements could create predictable demand that supports industry investment and growth.

A policy approach that supports both EVs and renewable fuels must not involve tradeoffs between the two pathways. Rather, a dual approach recognizes that different vehicle segments, use cases, and consumer profiles may be better served by different technologies. Long-haul transportation, for instance, presents significant challenges for electrification due to range and charging requirements, but it could readily adopt renewable fuels with minimal infrastructure changes. Different aspects of the transportation sector might be better decarbonized through one pathway over the other, and thus, a dual approach is most suitable for ensuring an economically viable transition.

Social Equity Considerations in Energy Transition

The social implications of different transition pathways deserve particular attention, especially regarding impacts across various socioeconomic groups. The current EV-focused approach implicitly requires consumers to purchase new vehicles to participate in the energy transition, creating a significant barrier for lower and middle-income households. Even with purchase incentives, the upfront cost of EVs remains prohibitive for many consumers, potentially creating a scenario where the benefits of the energy transition accrue primarily to higher-income households.

In contrast, a renewable fuels approach would allow consumers to continue using existing ICE vehicles while still reducing their carbon footprint. This pathway offers particular benefits for households that cannot afford a new vehicle purchase or lack access to home charging infrastructure. Without requiring capital-intensive vehicle replacement, equitable participation across the whole of society in the green energy transition can be ensured.

Furthermore, the manufacturing and supply chain implications of different transition pathways have important implications for employment and socio-economic development. The renewable fuels industry could create new jobs in collection, processing, and distribution that are more accessible to workers without requiring specialized technical training, allowing for even more of an equitable transition in decarbonizing the transportation sector.

Limitations and Future Research Directions

This analysis faces several limitations that suggest avenues for future research. First, technological developments in both EVs and renewable fuel production could significantly alter the economic analysis presented here. Breakthroughs in battery chemistry that reduce or eliminate dependency on rare earth metals or innovations in biodiesel production that increase yields or expand viable feedstocks could change the relative attractiveness of the different pathways.

Secondly, this analysis has primarily focused on the context of the U.S. auto industry, but global variations in resource availability, energy systems, and policy environments may lead to differing optimal strategies in different regions. The UN Environment Programme (2020) emphasizes the global nature of climate change, suggesting that regionally optimized solutions may be necessary to maximize impact and equitable green energy transitions.

Future research could address these limitations by developing more sophisticated models of technology adoption across different vehicle segments and consumer profiles, analyzing regional variations in optimal transition strategies, and exploring policy frameworks that effectively support complementary pathways rather than forcing binary choices between decarbonization technologies.

Conclusion

This research demonstrates that a dual approach incorporating both electric vehicles and renewable fuels, particularly waste-derived biodiesel, offers an equitable and sustainable pathway to decarbonizing the U.S. transportation sector. While EVs face significant challenges in achieving economies of scale due to rare earth metal demand constraints and high consumer costs, renewable fuels derived from waste streams face fewer resource limitations and enable society-wide participation without requiring vehicle replacement. The projected 30-40 fold increase in critical mineral demand for EVs by 2040 (International Energy Agency, 2021) will likely impede price reductions, while waste-derived biodiesel could potentially eliminate its current $0.41 per gallon premium over conventional diesel through targeted policy support and increased production scale. The broader significance of this research lies in demonstrating that transportation decarbonization must not solely rely on a single technological solution. Rather, policymakers should develop complementary strategies that leverage the advantages of both pathways—supporting EV adoption where appropriate while simultaneously expanding renewable fuel production to serve existing vehicle fleets. This integrated approach not only addresses environmental considerations but also ensures economic resilience and social equity in the transition to a carbon-neutral transportation sector.

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